# Higgs boson. Complete discovery and the window to a New Physics

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**Abstract**

1. We discuss the opportunities of complete Higgs boson discovery at different colliders. Main conclusion here is: Photon collider is the best for this goal.

2. We discuss how to use the Higgs boson (after its discovery) as the window to a New Physics. Main conclusion here is: Higgs boson production in gluon and photon fusion together with production in process $e\gamma \to eH$ provides very good window to a New Physics with the scale $\Lambda \gg M_H$ .

Among the main goals for future large colliders is the discovery of Higgs boson. In the Standard Model ($\mathcal{SM}$ ) Higgs boson is responsible for the observed breaking of the basic $SU(2) \times U(1)$ symmetry; the fundamental particles acquire masses through the interaction with scalar Higgs field. Until reliable discovery of Higgs we cannot believe that the $\mathcal{SM}$ is governed our world.

The construction of $\mathcal{SM}$ admits different variants of Higgs sector. Before symmetry breaking, Higgs fields can be several (weak) isotopical doublets, triplets etc. (in the $\mathcal{MSSM}$ — 2 doublets). In the minimal variant ($\mathcal{MSM}$ ) this Higgs field is single weak isodoublet. In our world, after symmetry breaking, Higgs sector contains one selfinteracting scalar and single free parameter of theory is its mass $M_H$ . In the 2–doublet model ($2\mathcal{DSM}$ ), after symmetry breaking the physical Higgs sector contains two neutral scalars, one neutral pseudoscalar ($\mathcal{CP}$ odd) (in some variants with scalar — pseudoscalar mixing and $\mathcal{CP}$ violation) and two charged Higgses. There is large variety in the possible couplings and sets of physical fields here. Besides, possible strong interaction in Higgs sector can produce various heavy "mesons" with $J^P = 0^-, 1^+, 2^\pm, ...$, which don't excluded by data so far. These opportunities should be excluded by forthcoming experiments to be sure that the discovered is indeed the Higgs boson of $\mathcal{MSM}$ or it represents some other model.

Our discussion is preceded brief description of different colliders for our aims since some features of a Photon and Muon colliders are badly known in community. Than we go to the physical problems noted in the abstract.

Through the paper we use the vacuum expectation value of Higgs field $v = 246$ GeV. We denote by $E$ and $\mathcal{L}$ the beam energy and annual luminosity of collider [1].

# 1 Colliders

The **Hadron colliders** are well known. That are upgraded Tevatron with $E = 1$ TeV, $\mathcal{L} = 2$ fb$^{-1}$ and LHC with $E = 7$ TeV, $\mathcal{L} = 100$ fb$^{-1}$.

**The Muon Collider ($\mu^+\mu^-$)** and its first stage – **First Muon Collider (FMC)** are under wide discussion now with the project parameters varied quickly. The most important for our problems is FMC with c.m.s. energy near $M_H$ , energy spread $100 \div 10$ MeV, annual luminosity 0.1 fb$^{-1}$ and beam polarization about 60%, which can be rotated relatively easily [2], [3]. At higher energy the potential of Muon Collider is close to that of $e^+e^-$ Linear Collider with the same energy.

**Next Linear Colliders in $e^+e^-$ mode** with beam energy $E_e = 0.25 \to 1$ TeV and annual luminosity $\mathcal{L} = 500$ fb$^{-1}$ are discussed in detail in refs. [4]. They will be complexes having $e^+e^-$ mode and **Photon Colliders ($\gamma e$ and $\gamma\gamma$ )** modes — **PLC** with following typical parameters [4, 5](*obtained without special optimization for photon mode*[1]):

- *Characteristic photon energy* $E_\gamma \approx 0.8E_e$.
- *Annual luminosity* $\mathcal{L} \approx 100$ *fb*$^{-1}$.
- *Mean energy spread* $< \Delta E_\gamma > \approx 0.07E_\gamma$.
- *Mean photon helicity* $< \lambda_\gamma > \approx 0.95$ *with easily variable sign. One can transform this polarization into the linear one [6].*
- *There are no reasons against observations at small angles* (except variable details of design).

# 2 Complete discovery of Higgs boson

In this section we consider Higgs boson in $\mathcal{MSM}$ . Some cloud of parameters of more complex models (two doublet, $\mathcal{MSSM}$ , ...) will be covered with the same efforts. In this respect one should solve the series of experimental problems:

1. *To discover something and to measure its mass.*
2. *To test that spin–parity* $J^P$ *is* $0^+$ *and to test* $\mathcal{CP}$ .
3. *To measure couplings with other particles.*
4. *To measure total width* $\Gamma_{tot}$.
5. *To measure Higgs selfcoupling constant.*

The potential of large colliders for the discovery of Higgs boson was studied in many papers. It is reviewed in refs. [7, 4],[8]–[10]. The most of properties of Higgs boson will be obtained by the combination of results from different colliders.

*The results obtained at some single collider are preferable for the discussed problem since an influence of systematical inaccuracies here can be reduced much more strong. In this respect, it is useful to compare the potential of different colliders for these problems.*

In the table 1 we collect main reactions and decay modes, useful for Higgs discovery. (The brackets [ ] shows decay modes that seem observable but they don't studied yet.)

The main mechanism of Higgs boson production at hadron colliders is *gluon fusion* $pp \Rightarrow gg \to H$. But the difficulties with background suppress often to use this channel

[1] One can obtain relatively easily $\mathcal{L}_{\gamma\gamma} \approx (0.2 \div 0.3)\mathcal{L}_{ee}$. Here $\mathcal{L}_{ee}$ is the luminosity of the initial $e^+e^-$ collider. With special efforts in the stage of damping rings or earlier the value of $\mathcal{L}_{\gamma\gamma}$ can be even larger than the basic $e^+e^-$ luminosity. The considered often opportunity to have higher $\mathcal{L}_{\gamma\gamma}$ with nonmonochromatic photon spectrum seems unsuitable for the physical program of PLC.

for Higgs boson discovery. So, for the hadron collider just as for the $e^+e^-$ collider the *associative production* of the Higgs boson in the states $ZH$, $WH$, $t\bar{t}H$, ... is considered mainly. The missing mass method in the reaction $e^+e^- \to HZ$ is noted below as MM. For the $\gamma\gamma$ and $\mu^+\mu^-$ colliders we consider the resonance production of Higgs boson ($\gamma\gamma \to H$ or $\mu^+\mu^- \to H$) only and show in the Table only the discovery channels.

| Collider$\to$ | $\bar{p}p,\ pp$ | | $e^+e^-$ | | $\gamma\gamma$ | $\mu^+\mu^-$ |
|---|---|---|---|---|---|---|
| $M_H\ GeV\downarrow$ | prod. | decay | prod. | decay | decay | decay |
| $95-130$ | $WH,\ ZH,$ $t\bar{t}H,\ gg\to H$ | $\tau\bar{\tau},$ $b\bar{b},\ \gamma\gamma$ | $ZH$ | MM, $b\bar{b}$ | $b\bar{b}$ | $b\bar{b}$ |
| $130-155$ | $gg\to H,\ WH,$ $t\bar{t}H$ | $[WW^*]$,$\tau\bar{\tau}$, $ZZ^*$, $\gamma\gamma$ | $ZH,$ $H\nu\bar{\nu}$ | MM, $b\bar{b}$, $[WW^*]$ | $WW^*$, $b\bar{b}$, $ZZ^*$ | |
| $155-180$ | $gg\to H$ | $WW,\ ZZ^*$ | $ZH,$ $H\nu\bar{\nu}$ | MM, $[WW]$, $ZZ^*$ | $WW^*$,$ZZ^*$ | |
| $>180$ | $gg\to H$ | $ZZ$ | $ZH,\ H\nu\bar{\nu}$ | $ZZ$, MM | $ZZ$, $[WW]$ | |

Table 1: *Production processes and discovery channels at different colliders.*

### 2.1 The separate problems at the discovery of Higgs boson

1. **The discovery of something and mass measurement** is the necessary first step. The $\mathcal{MSM}$ gives no definite predictions for $M_H$ . The vacuum stability of $\mathcal{MSM}$ limits $M_H$ from below by 105 GeV. The modern LEP data together with most probable estimate from the high–precision electroweak data gives for $\mathcal{MSM}$ $90 < M_H < 310$ GeV [1]. Higher values of $M_H$ are also not completely excluded. Contrary to that, if it will be found that $M_H > 130$ GeV, the $\mathcal{MSSM}$ is almost excluded.

The interval $M_H \le 95$ GeV will be covered at LEP2 in nearest future. The upgraded Tevatron + LEP2 promise to cover mass interval until $M_H = 130$ GeV.

For $M_H < 135$ GeV main decay channel is $H \to b\bar{b}$. It is expected to find such Higgs at Tevatron or $e^+e^-$ linear collider via the associative production or $\gamma\gamma$ decay channel for gluon fusion. The $\tau\bar{\tau}$ channel seems useful for LHC. The PLC and FMC have also high discovery potential in the $b\bar{b}$ channel.

If $M_H > 2M_Z$, Higgs can be discovered at all colliders via the sizable decay mode $H \to ZZ$. A background to this decay mode is rather small.

In the mass range $M_H = 140 - 190$ GeV the decay mode $H \to W^+W^-$ with real and virtual $W$ ($W^* \to q\bar{q}, e\bar{\nu}, ...$) is dominant, branching ratios of other decay modes become small, and their using for the Higgs boson discovery is difficult. The use of the $H \to W^+W^-$ decay at $e^+e^-$ collider is also difficult due to a strong nonresonant $WW^*$ background. The Higgs boson with the mass $M_H = 140 - 190$ GeV can be discovered at the PLC via the $H \to WW^*$ decay mode [11] with high efficiency. The potential of $ZZ^*$ channel here should be also considered.

The FMC provides opportunity to find Higgs boson mass with very high accuracy that determines by energy spread of collider. The price for this opportunity is the fact that this collider can find Higgs boson with $M_H < 200$ GeV only **after** discovery of some signal at another collider.

2. **Testing of spin–parity $J^P$ and $CP$ parity**. Besides the expected $\mathcal{MSM}$ Higgs boson we can meet axial $\mathcal{CP}$ odd Higgs partner from $2\mathcal{DSM}$ or $\mathcal{MSSM}$ and some

resonances from possible strong interaction in Higgs sector with $J^P = 0^\pm,\ 1^\pm,\ 2^\pm$. In any case, if $J^P \neq 0^+$ for the founded particle, it is not the Higgs boson. If the observed particle is pseudoscalar and it is decoupled with gauge bosons, one can hope that it is pseudoscalar Higgs partner from $2\mathcal{DSM}$ or $\mathcal{MSSM}$ .

*The $e^+e^-$ and hadron colliders.* When consider Higgs boson associative production the $ZZ$ final state gives quite different angular distribution than $ZH$. So, one can be sure that we cannot mix up H and Z. To exclude spin states like $J^P = 1^+,\, 2^\pm$ with similar angular dependencies at least large additional luminosity integral is needed. Besides, in $ZH$, $WH$ channels the angular distributions relative to $Z$, $W$ is changed dramatically with variation of the parity of produced scalar.

For the higher values of $M_H$ correspondent increasing of necessary energy of $e^+e^-$ collider is necessary and the observation process $e^+e^- \to HZ$ is changed to W–fusion $e^+e^- \to \nu\bar{\nu}H$. In this case testing of $J^P$ for the discovered particle needs difficult analysis of distributions of decay products.

*The PLC and FMC* allows the best opportunities to test spin and parity of produced particle via variation of initial polarization state of system.

Provided the luminosity distribution near the peak is the Lorencian one, the cross section of the (pseudo)scalar resonance production, averaged over luminosity distribution, is ($C = \gamma\gamma$ or $\mu^+\mu^-$) (sign "$+$" corresponds scalar, sign "$-$" corresponds pseudoscalar).

$$\begin{gathered}
<\sigma_C>= \int \sigma(s)\frac{1}{\mathcal{L}}\frac{d\mathcal{L}}{ds}ds \equiv B_C\cdot\frac{4\pi\Gamma_{H\to A}}{M_H^3}\left[1+\lambda_1\lambda_2\pm D_\perp\right],\\
B_C=\frac{1}{\pi}\frac{M_H}{\Gamma_H+\Delta E};\\
4\pi\frac{\Gamma_{H\to\mu\mu}}{M_H^3}=\frac{m_\mu^2}{2v^2M_H^2},\quad 4\pi\frac{\Gamma_{H\to\gamma\gamma}}{M_H^3}=\left(\frac{\alpha}{4\pi}\right)^2\frac{|\Phi|^2}{4v^2}\quad(|\Phi|\sim 1);\\
D_\perp=\ell_1\ell_2\cos 2\phi\ \text{ for }\gamma\gamma\,,\quad D_\perp=4\vec{s}_{1\perp}\vec{s}_{2\perp}\ \text{ for }\mu^+\mu^-\,.
\end{gathered}\tag{1}$$

Here $\Delta E$ is the initial energy spread, $\lambda_i$ are the helicities of photons or doubled helicities of muons, $\ell_i$ are degrees of photon linear polarization and $\phi$ is the angle between them, $\vec{s}_{i\perp}$ are transverse components of muon spin[2].

Therefore variation of sign of helicity of one photon or muon switches on or off the production of "Higgs boson". Such experiment excludes completely states with $J^P = 1^\pm,\ 2^\pm$. The variation of linear (transverse) polarizations switches on or off particle production depending on its parity. The necessary luminosity integral here is the same as for the discovery of the particle. The PLC is better for these problems due to possible earlier beginning of operations and higher degree of beam polarization expected.

3. **Coupling of Higgs boson with other particles**. The Higgs mechanism of particle mass origin in the $\mathcal{MSM}$ means that the coupling constant of Higgs boson with the fundamental particle $f$ is given by the ratio of its mass to the vacuum expectation value of Higgs field $v$ (for fermions), $g_f = m_f/v$. If the observed value will be different, then either some model with many Higgses (e.g. $\mathcal{MSSM}$ ) is valid or the mechanism of mass origin in $\mathcal{SM}$ differs from that considered in this model.

To measure these couplings (their ratios) one should resolve Higgs boson signal in both the dominant decay mode and in another modes. The nonresonant production of these final states gives very high background. This background is suppressed in the resonance

[2] Note that $\alpha/4\pi \sim m_\mu/v$. So the difference between averaged cross sections at PLC and FMC is given mainly by the collider quality factor $B_C$.

production of narrow Higgs boson with not too high mass. Here the position of FMC seems the best.

Good potential (which is not studied in detail yet) has here the PLC. For example, about 10 fb$^{-1}$ is necessary to see decay $H \to ZZ^*$ at $M_H > 120$ GeV [11]. So, one can find the ratio $g_{HZZ}/g_{HWW}$. If Higgs mass is within interval 125–150 GeV, one can measure additionally $g_{Hb\bar{b}}/g_{HWW}$, etc. This interval is the best for testing of many coupling constants of Higgs boson at PLC.

The Table 1 shows the potential of different colliders in this problem. The measuring of separate coupling constants and Higgs selfcoupling are very difficult problems at $e^+e^-$ or proton colliders. It needs very high luminosity integral.

4. **The total Higgs width** $\Gamma_H$ in the $\mathcal{MSM}$ is calculated with high accuracy via $M_H$ and the set of fundamental particle masses. $\Gamma_H < 10$ MeV at $M_H < 140$ GeV, $\Gamma_H < 10$ GeV at $M_H > 310$ GeV, $\Gamma_H/M_H > 1/4$ at $M_H > 700$ GeV.

One can hope to measure $\Gamma_H$ at $M_H > 200$ GeV at all colliders. At $M_H < 200$ GeV this quantity can be measured directly at FMC only. In the mass interval $M_H = 180 - 210$ GeV the cross section of process $\gamma\gamma \to WW$ exhibit specific structure obliged by interference of QED process with Higgs. With resolution about 5 GeV in the $WW$ effective mass this structure can be used to both see Higgs boson and to measure its width.

5. **The Higgs selfinteraction** $\lambda^2(aH^3 + H^4)/8$ is the basic point of Higgs mechanism. The $\mathcal{MSM}$ constants are $\lambda = M_H/v$, $a = 2v$. This selfinteraction can be seen in the processes $e^+e^- \to ZHH$, $e^+e^- \to \nu\bar{\nu}HH$, $\mu^+\mu^- \to \nu\bar{\nu}HH$, $\gamma\gamma \to WWHH$, $\gamma\gamma \to HH$, $\gamma\gamma \to HH$, etc. with cross section about 1 fb or less [12, 13]. In these cross sections the diagrams with HHH vertex compensate strong those without this vertex. So, the result is sensitive to the possible deviations from above value of this constant.

**General view.** The expected opportunities to study different properties of Higgs boson are shown in the Table 2. When 2 signs are in one square of this table, the upper corresponds $M_H < 200$ GeV, the lower – 500 GeV$> M_H >$ 200 GeV.

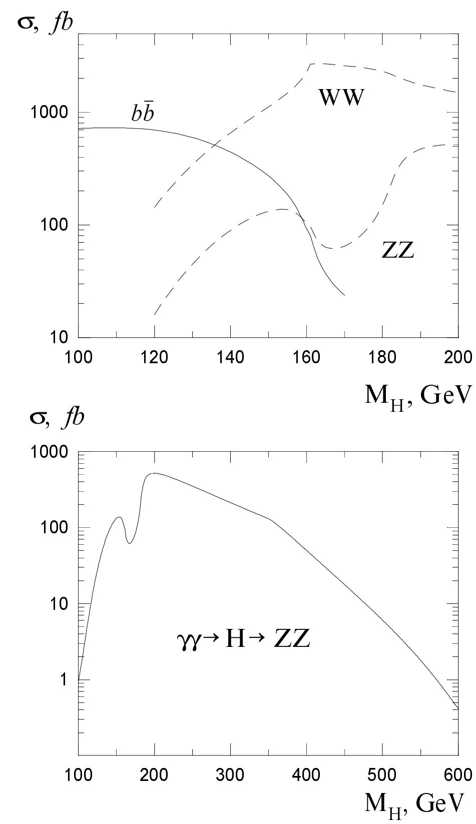


Figure 1: *The cross section of reaction $\gamma\gamma \to H$ with some decay channels. $<\lambda_1> = <\lambda_2> = 0.9$; $20^\circ < \theta < 160^\circ$.*

One can conclude that the PLC and FMC are the best in complete discovery of Higgs boson with some advantages for PLC. The analysis of the data in Z peak and estimates in $\mathcal{MSSM}$ show that the most probable mass interval for Higgs boson is $100 \div 200$ GeV. So, as it was proposed earlier, the PLC with the c.m.s. energy 100–200 GeV open the shortest way to find Higgs boson and to test its properties completely [14].

To estimate necessary luminosity integral $\int \mathcal{L}$ for the discovery of Higgs boson at PLC we assume sequence of runs covered about 10% of energy interval near the upper bound. Fig. 1 represent the Higgs boson production cross sections for different essential channels.

| *problem* | Tevatron /LHC | $e^+e^-$ collider | Photon collider | FMC |
|---|---|---|---|---|
| 1 discovery | $+$ | $+$ | $+$ | $-$<br>$\pm$ |
| Mass | $+$ | $+$ | $+$ | The best |
| Spin–Parity | $\neq Z$, $\neq 0^-$<br>$\pm$ | $\neq Z, \neq 0^-$<br>$\pm$ | $J^P \neq 0^+$ excluded | |
| $\Gamma_{tot}$ | —<br>$+$ | —<br>$+$ | Poor<br>$+$ | The best |
| Couplings | $\pm$ | $\pm$ | $\pm$ | $+$<br>$\pm$ |
| Selfinteraction | Poor | $\pm$ | $\pm$ | $\pm$ |

Table 2: *Potential of Higgs boson complete discovery.*

The first discovery of Higgs here demands less than 3 fb$^{-1}$ for suitable energy interval[3] Therefore, to cover mass interval 100–200 GeV one should have $\int \mathcal{L} < 15$ fb$^{-1}$. After discovery of Higgs peak, the same luminosity integral (no more than 3 fb$^{-1}$) is necessary to test spin and parity of this particle via the change of polarization (see eq. (1)).

In the mass interval 200–300 GeV main discovery channel is $\gamma\gamma \to ZZ$ with $\int \mathcal{L} \approx 1$ fb$^{-1}$ for each energy interval. So $\int \mathcal{L} < 5$ fb$^{-1}$ is necessary to cover whole discussed region. The additional integral about 2 fb$^{-1}$ is necessary to test spin and parity here.

At $M_H > 350$ GeV Higgs signal should be resolved at the *regular* loop induced background $\gamma\gamma \to ZZ$. Here the luminosity integral about $10 \div 20$ fb$^{-1}$ is sufficient to see signal from the Higgs boson (which will be obtained at LHC before these measurements).

# 3 Higgs window to a New Physics

Going to higher energies we hope to meet New Physics with characteristic scale $\Lambda > 1$ TeV. Before discovery new heavy particles inherent this New Physics, it reveals itself at lower energies as some *anomalies* in the interactions of known particles. The goal of studies in this field is to find these anomalous interactions and discriminate as better as possible the type of underlying theory via comparison of different anomalies.

**After discovery of Higgs boson the study of gluon fusion at hadron collider, processes $\gamma\gamma \to H$ and $e\gamma \to eH$ at photon colliders will provide the best place for discovery and discrimination of New Physics effects.** Indeed,

- *The $Hgg$, $H\gamma\gamma$, $H\gamma Z$ vertices are absent in the $\mathcal{SM}$ Lagrangian. They are one–loop effects. Therefore, the relative contribution of anomalies is enhanced here in comparison with other interactions.*
- *If New Physics adds new heavy particles into the $\mathcal{SM}$ , their effects are enhanced in the discussed vertices due to absence of decoupling here.*
- *Gluon or photon fusion are dominant mechanisms of Higgs boson production at hadron or photon colliders.*

[3] If $M_H < 145$ GeV, the discovery of Higgs boson via reaction $\gamma\gamma \to b\bar{b}$ demands $\int \mathcal{L} < 3$ fb$^{-1}$ [15]. If $135 < M_H < 195$ GeV, the discovery of Higgs boson via reaction $\gamma\gamma \to WW^*$ demands $\int \mathcal{L} < 1$ fb$^{-1}$ [11]. If $M_H > 185$ GeV, the discovery of Higgs boson via reaction $\gamma\gamma \to ZZ$ demands $\int \mathcal{L} < 1$ fb$^{-1}$.

The gluon fusion at Hadron Collider and photon fusion at PLC are studied good in literature. The $e\gamma \to eH$ process provides opportunity to study $HZ\gamma$ interaction after the study of $H\gamma\gamma$ interaction in the process $\gamma\gamma \to H$.

It is useful to describe briefly why decoupling is absent in this problem. It is very simple and well known (see e.g. [16]). The Higgs two–gluon decay is the loop effect with quarks in loop. The contribution of each quark in the amplitude is proportional to $g_q\alpha_s/max\{M_H, m_q\}$. The Higgs–quark Yukawa coupling constant here $g_q = m_q/v(m_q$ is the quark mass). Therefore, at $m_q < M_H$ this contribution is small and at $m_q > M_H$ each quark gives the same contribution independent on its mass. This vertex counts number of quarks that are heavier than the Higgs boson. The same is valid for the $H\gamma\gamma$ and $HZ\gamma$ interactions, but here the charged leptons and gauge bosons also contribute in the amplitude, and contributions of fermions and gauge bosons have opposite sign. That is why Higgs boson fusion is very sensitive to the new heavy particles having Higgs mechanism of mass origin. (If the mass of heavy particle arises not via Higgs mechanism, it is decoupled with the relatively light Higgs boson.)

Below we discuss some scenarios of New Physics from this point of view.

### 3.1 Search of fourth generation [17]

The $\mathcal{SM}$ does not fix the number of generations of quarks and leptons. There are no ideas, why there is more than one generation and what Law of Nature limits their number.

The studies at Z peak at LEP closed the window for the 4–th generation quarks and leptons with light neutrino. However, the extra generations with heavy neutrino does not excluded. The above data shows that if this generation exists, the quarks and leptons within should be much heavier than 200 GeV and neutrino is heavier than 45 GeV.

Fortunately, *one can answer definitely about existence of these families before the discovery their very heavy members* via the study of gluon and photon fusion of the Higgs boson at proton and photon colliders.

Due to absence of decoupling here, one can consider for the gluon fusion at Tevatron and LHC only the effects of $t$–quark and 4–th generation. Then for the Higgs with mass less 200 GeV the amplitude increases by a factor 3 and the two–gluon width – by a factor 9. At higher Higgs masses more detail effects near $t\bar{t}$ threshold become essential.

The experimental cross sections is the convolution of the cross section of the fusion Higgs production with gluon structure functions. The variations in the production cross sections for the different decay channels obtained with the structure functions [18] shown in the Fig. 2. Here two gluon width and production cross section in the model with n generations are labeled by superscript $n$[4].

It is seen that the effect at proton collider is huge. This Figure shows the opportunity to find effect of 4–th generation in different channels at hadron colliders[5]. In respect of studies at relatively light Higgs boson we compare here also the Higgs boson production in $\tau\bar{\tau}$ channel and the corresponding background ($q\bar{q} \to Z \to \tau\bar{\tau}$). One can see that the signal from fourth generation should be seen at upgraded Tevatron in $WW^*$ channel

[4] Here only one–loop are presented. The QCD radiative corrections enhance cross section (but no background) by a factor about 2. Radiative corrections due to strong Yukawa interaction of Higgs field with heavy matter was not considered.

[5] The radiative corrections enhances these cross sections strongly. The detector efficiency effects reduce these cross sections. But their relations are independent from detail of recording.


Figure 2: *The cross sections of Higgs boson production at Tevatron and LHC for different decay channels. The lower curves — three generations, the upper ones — four generations. The $\tau\bar{\tau}$ background is also shown.*

till 190 GeV. The studies of $\tau\bar{\tau}$ production at effective masses below 150 GeV and of $WW^*$ production above 135 GeV could reveal the existence of the fourth generation even without discovering the Higgs boson in the associative production. Studies at LHC cover whole possible set of the $M_H$ values.

The discussed large effect for gluon fusion can be imitated in two Higgs doublet models or in $\mathcal{MSSM}$ at $\tan\beta \approx 20$. To exclude this explanation, the two photon production of Higgs boson at PLC should be considered. In this reaction contributions of fermion and $W$ loops are of opposite sign below corresponding thresholds. It is the reason why cross section of photon fusion is decreased strongly at $M_H < 300$ GeV as compare with standard case. In this case 2-doublet model imitate effect at the different value of $\beta$. Therefore to measure Higgs boson production at photon collider is necessary to confirm that effect is connected with new generation. The additional measurements of $e\gamma \to eH$ reaction are also useful for this goal. Figs. 3 and 4 shows effect of new heavy generation in these processes.

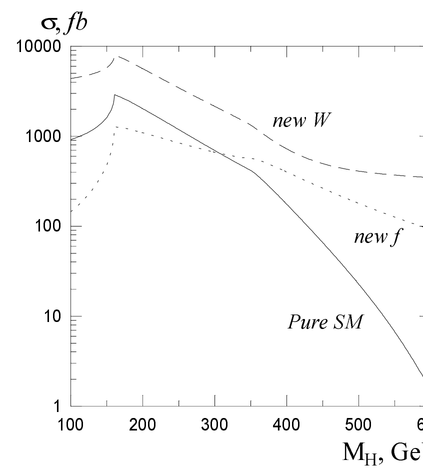


Figure 3: *The effect of new particles within $\mathcal{SM}$ on $\gamma\gamma \to H$ cross section. $<\lambda_1>=<\lambda_2>=0.9$; $20^\circ < \theta < 160^\circ$.*

The effect of possible new heavy $W$ – like boson in the Higgs boson production at PLC is also shown in Fig. 3. To verify this mechanism, additional measurements of $e\gamma \to eH$ process are necessary (this new $W$ gives no contribution in the gluon fusion.)

## 3.2 Two doublet $\mathcal{SM}$ – 2$\mathcal{DSM}$

The simplest extension of $\mathcal{MSM}$ — 2$\mathcal{DSM}$ — contains two doublet Higgs sector. Let us remind that its real Higgs sector contains 2 neutral scalars $h$ (light) and $H$ (heavy), one neutral pseudoscalar $A$ and two charged Higgses $^{\pm}$ and some set of Yukawa couplings with the matter fields. The key parameters of model are two mixing angles $\beta$ and $\alpha$. We assume below the widely discussed Model II for the Yukawa coupling of Higgs fields with the matter fields.

The observation of coupling of Higgs boson with other particles different from that predicted by $\mathcal{MSM}$ would be strong argument in favor of 2$\mathcal{DSM}$ . However, it is difficult to expect complete enough set of observed couplings to conclude about realization of 2$\mathcal{DSM}$ definitely. The discovery of all Higgs particles would be essential step in this problem.

We discuss the nearest opportunities related to the case of 2$\mathcal{DSM}$ in which the argumentation in favor of model different from $\mathcal{MSM}$ cannot be obtained. That are the cases when either the lightest Higgs $h$ (pseudoscalar $A$) cannot be seen or observed $h$ imitate Higgs boson of $\mathcal{MSM}$ . In both cases we assume masses of other Higgses to be much higher than $M_h$.

A. If $\sin^2(\beta-\alpha) < 0.1$, the relatively light $h$ or $A$ ($2\div 50$ GeV) can exist but elusive for modern experimentation. There is wide enough field of parameters for this elusive Higgs boson [19]. This boson can be seen either in the processes like $e^+e^- \to t\bar{t}H$, $\gamma\gamma \to t\bar{t}H$ (at large enough $\cot\beta$).

The reliable method to see such Higgs boson is to study it via loop obliged processes where effects of different quarks supplement each other. The first idea was to use for this goal photon fusion [19]. However, the necessary low energy photon collider doesn't considered now as realistic future machine. The other way is to use process $\gamma e \to eh$ or $\gamma e \to eA$ at $\gamma e$ collider with c.m.s. energy 100-400 GeV [20]. One can expect here effect about 10 fb or larger [21].

B. Another opportunity is 2$\mathcal{DSM}$ , imitating $\mathcal{MSM}$ . It corresponds $\sin(\beta-\alpha) = 1$. In this case all couplings of $h$ with the matter are the same as in $\mathcal{MSM}$ . For the first glance, there is no opportunity to exclude this variant before discovery of $A$, $H$, $H^{\pm}$. Fortunately, the coupling with photons is sensitive to the existence of heavy charged Higgs bosons. So, the comparative study of gluon fusion and photon fusion together with $e\gamma \to eH$ process ($HZ\gamma$ vertex) will resolve such 2$\mathcal{DSM}$ from $\mathcal{MSM}$ [22].

The next problem is – **how to distinguish 2$\mathcal{DSM}$ from $\mathcal{MSSM}$ before discovery (heavy) superpartners**. This problem become essential after obtaining of some experimental argumentation against $\mathcal{MSM}$ . Since the variety of possible parameters of 2$\mathcal{DSM}$ is large, the solution of this problem can be obtained through comparison of couplings of Higgs bosons with gluons and photons (perhaps for all three, $h$, $H$ and $A$) [22].

## 3.3 Anomalous interactions in Higgs boson production at $\gamma\gamma$ and $\gamma e$ collisions

At energies below scale of New Physics $\Lambda$ this New Physics manifests itself as some (*anomalies*) in the interactions of known particles. It can be described by an effective

Lagrangian which is written as expansion in $\Lambda^{-1}$ (For the observable effects it means expansion in $(E/\Lambda)$):

$$L_{eff} = L_{SM} + \sum_{k=1}^{\infty} \Delta L_k\,; \quad \Delta L_k = \sum_r \frac{d_{rk}\mathcal{O}_{rk}}{\Lambda^k}\,, \quad (dim\{\mathcal{O}_{rk}\} = 4 + k\,). \tag{2}$$

Here $L_{SM}$ is the Lagrangian of the $\mathcal{SM}$ . Below, as usual,

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu\,, \quad W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\epsilon^{ijk} W^j_\mu W^k_\nu\,; \quad \tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\mu\alpha\beta} V_{\alpha\beta}\,.$$

We have $\Delta L_1 = 0$. Therefore, we consider the next largest term $\Delta L_2$. For our problem contributions of different items $\mathcal{O}_{r2}$ are joined in the

$$\Delta L_v = (2Hv + H^2)\left(\theta_\gamma \frac{F_{\mu\nu}F^{\mu\nu}}{2\Lambda_\gamma^2} + i\tilde{\theta}_\gamma \frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\Lambda_{P\gamma}^2} + +\theta_Z \frac{Z_{\mu\nu}F^{\mu\nu}}{\Lambda_Z^2} + i\tilde{\theta}_Z \frac{Z_{\mu\nu}\tilde{F}^{\mu\nu}}{\Lambda_{PZ}^2}\right) \quad [\theta_i = \pm 1]\,. \tag{3}$$

The relation of these new scales with those of initial Lagrangian is obtained easily.

It is useful to write the necessary item in the effective Lagrangian for Higgs field interaction with electromagnetic field (including the $\mathcal{SM}$ contribution) in the form:

$$\mathcal{L}_{H\gamma\gamma} = \frac{\left[G_\gamma H F^{\mu\nu} F_{\mu\nu} + i\tilde{G}_\gamma H F^{\mu\nu} \tilde{F}_{\mu\nu}\right]}{2v}\,, \quad \mathcal{L}_{HZ\gamma} = \frac{\left[G_Z H F^{\mu\nu} Z_{\mu\nu} + i\tilde{G}_Z H F^{\mu\nu} \tilde{Z}_{\mu\nu}\right]}{v}\,. \tag{4}$$

with coupling "constants"

$$G_i = G_i^{SM} + \theta_i \frac{v^2}{\Lambda_i^2}\,, \quad \tilde{G}_i = \tilde{G}_i^{SM} + \tilde{\theta}_i \frac{v^2}{\Lambda_{Pi}^2}\,. \tag{5}$$

The $\mathcal{SM}$ values of these couplings are well known (see e.g. [8, 10]).

In the $\mathcal{MSM}$ we have $\tilde{G}_i^{SM} = 0$. In the extended $\mathcal{SM}$ (e.g. in $2\mathcal{DSM}$ ) scalar and pseudoscalar Higgs field can be mixed, in this case additionally $Im\tilde{G}_i^{SM} \neq 0$ at $M_H > 2M_t$.

**The process $\gamma\gamma \to H$ provides the best place for the study of $H\gamma\gamma$ anomalies** [23, 21, 24]. The cross section of process averaged over the photon spectrum is (cf. (1 and notations there):

$$\begin{gathered}
<\sigma> = <\sigma>_{np}^{SM} \frac{T(\lambda,\phi)}{|G_\gamma^{SM}|^2}\,, \\
T(\lambda,\phi) = \left(|G_\gamma|^2 + |\tilde{G}_\gamma|^2\right)(1 + \lambda_1\lambda_2) + \left(|G_\gamma|^2 - |\tilde{G}_\gamma|^2\right)\ell_{T1}\ell_{T2}\cos 2\phi\ 0 \\
+2Re(G_\gamma^*\tilde{G}_\gamma)(\lambda_1 + \lambda_2) + 2Im(G_\gamma^*\tilde{G}_\gamma)\ell_{T1}\ell_{T2}\sin 2\phi\,.
\end{gathered} \tag{6}$$

The effect of $\mathcal{CP}$ even anomalies (neglecting $\mathcal{CP}$ odd) is shown in Fig. 4. It is seen that the two–photon production cross section is sensitive to the anomalies with the scale $\Lambda = 20 - 25$ TeV for the most probable Higgs boson mass.

The earlier estimates of possible sensitivity to the $\mathcal{CP}$ odd anomalies without detail study of interference are incorrect since effect $|\tilde{G}_\gamma|^2 \propto 1/\Lambda^4$ is of the same order of value as the contribution of 8-th order $\mathcal{CP}$ even operator in $|\tilde{G}_\gamma|^2$ item.

It is seen that the interference $\mathcal{CP}$ odd item with the basic $\mathcal{CP}$ even one should be clearly seen via variation of cross section with variation of signs of both photon helicities

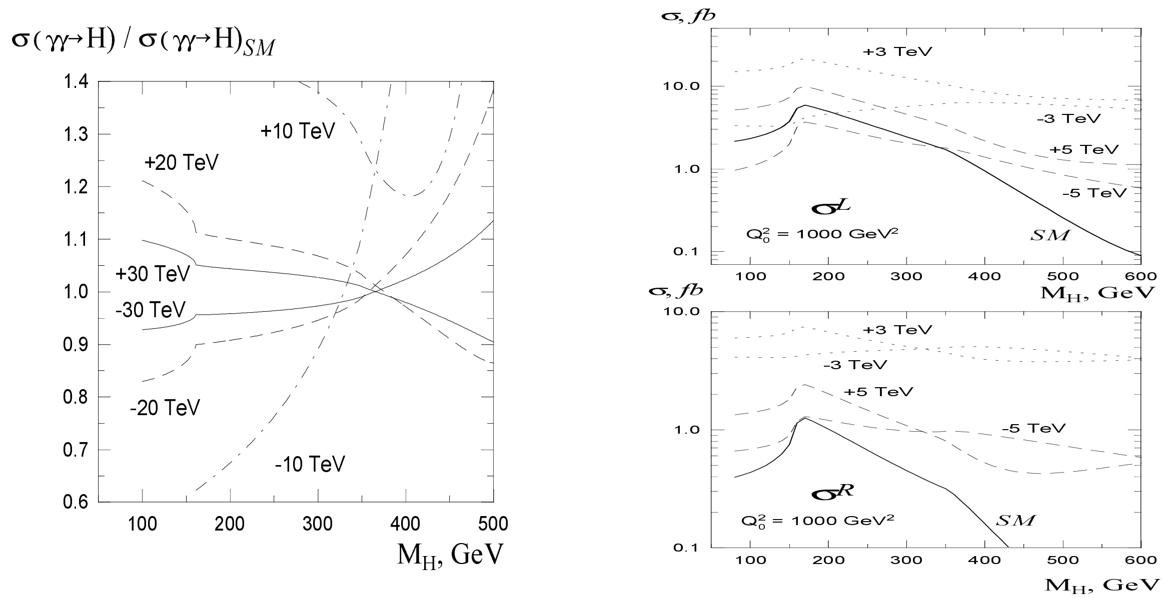


Figure 4: *The modification of the $\gamma\gamma \to H$ cross section caused by $H\gamma\gamma$ anomaly and cross sections $\sigma_L$ and $\sigma_R$ of $e\gamma \to eH$ process caused by $Z\gamma H$ anomaly. The numbers denote $\theta_i\Lambda_i$.*

simultaneously (both left $\Rightarrow$ both right) and via the study of production cross section dependence on the angle between directions of linear polarizations $\phi$.

**The process $e\gamma \to eH$ provides the best place for the study of $HZ\gamma$ anomalies** after the study of $H\gamma\gamma$ anomaly in the process $\gamma\gamma \to H$ [23, 21, 24].

Let us start from description of $\mathcal{SM}$ case [21, 25]. We consider the process amplitude only for real ingoing photon. It is a sum of three items. The first one, $\mathcal{A}_\gamma$, is the $\gamma$ exchange contribution (photon exchange between scattered electron and triangle loop describing $\gamma^*\gamma \to H$ subprocess). This item is evidently gauge–invariant since longitudinal item in photon propagator gives in the electron vertex $q^\mu u(p')\gamma^\mu u(p) \to u(p')(\hat{p}-\hat{p}')u(p) = 0$. The second item is the $Z$ – exchange contribution $\mathcal{A}_Z$ ($Z$–boson exchange between scattered electron and triangle loop describing $Z^*\gamma \to H$ subprocess). This item is *approximately* gauge–invariant with accuracy $\sim m_e/M_Z$. The residual item (we denote it as box) is, consequently, gauge–invariant with this very accuracy. Calculations show that its contribution is small in comparison with each pole contribution.

The effects of photon and $Z$ exchange are dominant in the total cross section. The numerical analysis shows that the effects of $Z$ exchange become close to that of photon exchange in the cross section integrated over the region of the transverse momenta of scattered electrons $p_\perp \ge p_{\perp 0} \approx 30$ GeV. Besides, these contributions almost compensate each other in the cross section for the right hand polarized electrons and they interfere constructively. The corresponding cross section is about 10 fb.

These figures show the opportunity to see effect of $HZ\gamma$ interaction in the $e\gamma \to eH$ process.

**Effect of $HZ\gamma$ anomalies** in $e\gamma \to eH$ process is studied in [21, 24]. The opportunity to see effects of $\mathcal{CP}$ even anomalies (neglecting $\mathcal{CP}$ odd) is seen from Fig. 4. It is seen that one can expect to see anomalies with the scale $\Lambda \approx 4 - 5$ TeV.

The effect of $\mathcal{CP}$ odd anomalies can be studied via the polarization dependence of cross section which reproduces main features of cross section (3.3). To understand the

result one should take into account that the linear polarization of virtual photon or $Z$ is directed in its scattering plane and its circular polarization is about $(M_h^2/s)2\Lambda_e$ where $\lambda_e$ is helicity of electron [26]. Therefore, the effect of $\mathcal{CP}$ odd anomalies can be seen via the study dependence of cross section on the sign of photon helicity and on the angle between electron scattering plane angle relative to the direction of photon linear polarization.

The possible limits for new $\mathcal{CP}$ odd and $HZ\gamma$ effects will be enhanced if some anomalous $H\gamma\gamma$ effects exist.

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